REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 28-02-2012	**2. REPORT TYPE** Final progress report	**3. DATES COVERED** *(From - To)* March 1, 2009 - November 30, 2011

4. TITLE AND SUBTITLE
Tools for multivariable spectral and coherence analysis

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-09-1-0113

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Tryphon T. Georgiou

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Minnesota

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
Suite 325, Room 3112
875 Randolph Street
Arlington, VA 22203-1768

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-OSR-VA-TR-2012-0992

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution A - Approved for Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The aim of this research has been to develop quantitative tools for high resolution signal analysis and system modeling. These consist of theory and software. An important contribution has been to introduce a family of distance metrics to be used for comparing power spectral distributions in multivariable time-series. These metrics allow quantitative assessment of uncertainty and of resolution in spectral analysis. They also provide a geometric substrate for new techniques in filtering and estimation. More specifically, the concepts of geodesics and that of geometric means, have provided models for time-varying spectra and for ways to aggregate information from disparate sources, respectively. A description of software developed is maintained at the PI's website (http://www.ece.umn.edu/~georgiou/files/software.html).

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Tryphon T. Georgiou
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	7	**19b. TELEPHONE NUMBER** *(include area code)* (651) 470-2037

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Final Report

Tools for Multivariable Spectral and Coherence Analysis

submitted to the

Air Force Office of Scientific Research

performed under

AFOSR Grant FA9550-09-1-0113

Tryphon T. Georgiou
Principle Investigator
Department of Electrical
& Computer Engineering
University of Minnesota-Twin Cities
tryphon@umn.edu

February 2012

Contents

1 Summary

The aim of this research has been to develop quantitative tools for high resolution signal analysis and system modeling. These consist of theory and software. An important contribution has been to introduce a family of distance metrics to be used for comparing power spectral distributions in multivariable time-series. These metrics allow quantitative assessment of uncertainty and of resolution in spectral analysis. They also provide a geometric substrate for new techniques in filtering and estimation. More specifically, the concepts of geodesics and that of geometric means, have provided models for time-varying spectra and for ways to aggregate information from disparate sources, respectively. A description of concepts and of the software that emerged is included and maintained at the PI's website (http://www.ece.umn.edu/˜ georgiou/files/software.html).

2 Research Publications (2009-2011)

2.1 Journal publications

1. T.T.Georgiou, J. Karlsson, and S. Takyar,"Metrics for power spectra: an axiomatic approach," *IEEE Trans. on Signal Processing,* **57(3)**: 859 - 867, 2009.

2. V.L. Bageshwar, D. Gebre-Egziabher, W.L. Garrard, and T.T. Georgiou, Stochastic Observability Test for Discrete-Time Kalman Filters, *AIAA Journal of Guidance, Control, and Dynamics*, 32(4): 1356-1370, 2009.

3. T.T. Georgiou and M.C. Smith, "Feedback Control and the Arrow of Time," *International Journal of Control*, **83(7)**: 1325 1338, 2010.

4. J.Karlsson, T.T. Georgiou, and A. Lindquist, "The Inverse Problem of Analytic Interpolation with Degree Constraint and Weight Selection for Control Synthesis," *IEEE Trans. on Automatic Control*, **55(2)**: 405-418, 2010.

5. Mir Shahrouz Takyar, and T.T. Georgiou, "Multivariable analytic interpolation with a degree constraint," *IEEE Trans. on Automatic Control*, **55(5)**: 1057-1088, 2010.

6. F. Carli and T.T. Georgiou "On the Covariance Completion Problem under a Circulant Structure," *IEEE Trans. on Automatic Control*, **56(4)**: 918 - 922, 2011.

7. Xianhua Jiang, Zhi-Quan (Tom) Luo and Tryphon T. Georgiou, "Geometric Methods for Spectral Analysis," *IEEE Trans. on Signal Processing,* 60(3): 1064-1074, 2012.

8. Xianhua Jiang, Lipeng Ning, and Tryphon T. Georgiou, "Distances and Riemannian metrics for multivariate spectral densities," *IEEE Trans. on Automatic Control*, to appear in 2012, (http://http://arxiv.org/abs/1107.1345v1)

9. T.T. Georgiou and A. Lindquist, "The Separation Principle in Stochastic Control, Redux," under review, (http://arxiv.org/abs/1103.3005)

10. Lipeng Ning, Xianhua Jiang and Tryphon Georgiou, "Geometric methods for estimation of structured covariances," under review (http://arxiv.org/abs/1110.3695)

11. J.Karlsson and T.T. Georgiou, "Uncertainty bounds for spectral estimation," under review (http://arxiv.org/401938).

2.2 Book chapters

12. T.T. Georgiou and A. Tannenbaum, "Sparse Blind Source Deconvolution with Application to High Resolution Frequency Analysis", in *Three Decades of Progress in Systems and Control*, Hu, X.; Jonsson, U.; Wahlberg, B.; Ghosh, B. (Eds.), Springer-Verlag, 2009.

13. T.T. Georgiou and A. Tannenbaum, "Sparse Blind Source Deconvolution via ℓ_1-norm Optimization", in *Perspectives in Mathematical System Theory, Control, and Signal Processing*, J.C. Willems, S. Hara, Y. Ohta, and H. Fujioka (Eds.), pages 321-330, Springer-Verlag, 2010.

14. E. Tannenbaum, T.T. Georgiou, and A. Tannenbaum, "Optimal Mass Transport for Problems in Control, Statistical Estimation, and Image Analysis," Srpinger-Verlag, to appear, 2012.

15. M.S. Takyar and T.T. Georgiou, "Fractional-order systems and the internal model principle," Springer-Verlag, to appear, 2012.

2.3 Conference proceedings

16. K. Georgiou and T.T. Georgiou, "Graceful switching in hybrid models," *48th IEEE Conference on Decision and Control*, Shanghai, China, December 2009.

17. L. Ning, T.T. Georgiou, and A. Tannenbaum, "High resolution analysis via sparsity-inducing techniques: spectral lines in colored noise," Intern. Symposium on Mathematical Theory of Networks and Systems, Hungary, July 2010.

18. D. Rudoy and T.T. Georgiou, Nonstationary Processes and Spectral Distances, Intern. Symposium on Mathematical Theory of Networks and Systems, Hungary, July 2010.

19. F. Carli and T.T. Georgiou "On the Covariance Completion Problem under a Circulant Structure," Intern. Symposium on Mathematical Theory of Networks and Systems, Hungary, July 2010.

20. P. Stoica, L. Du, J. Li, Tryphon Georgiou, "A New Method for Moving-Average Parameter Estimation," 44th Asilomar Conference on Signals, Systems and Computers, Asilomar Conference Grounds, Pacific Grove, California, November 2010.

21. M. Jovanovic and T. Georgiou, "Reproducing second order statistics of turbulent flows using linearized Navier-Stokes equations with forcing," Bulletin of the American Physical Society, 63rd Annual Meeting of the APS Division of Fluid Dynamics, vol. 55(16), (abstract), 2010.

22. D. Li, N. Hovakimyan, T.T. Georgiou, Robustness of L1 Adaptive Controllers in the Gap Metric in the Presence of Nonzero Initialization, IEEE Conference on Decision and Control, Atlanta, pages 2723 - 2728, December 2010.

23. D. Li, N. Hovakimyan, T.T. Georgiou, "Robustness of L1 adaptive controllers in the gap metric," American Control Conference (ACC), pages 3247 - 3252, 2010.

24. L. Ning, T.T. Georgiou and A. Tannenbaum, Separation of system dynamics and line spectra via sparse representation, IEEE Conference on Decision and Control, Atlanta, pages: 473 - 478, December 2010.

25. E. Tannenbaum, T.T. Georgiou, A. Tannenbaum, Signals & Control Aspects of Optimal Mass Transport and the Boltzmann Entropy, IEEE Conference on Decision and Control, Atlanta, 1885 - 1890, December 2010.

26. L. Ning and T.T. Georgiou, Sparse factor analysis via likelihood and ℓ_1-regularization, IEEE Conference on Decision and Control, Orlando, Florida, December 2011.

27. Xianhua Jiang, Lipeng Ning and Tryphon T. Georgiou, "Geometric methods for structured covariance estimation," American Control Conf., to appear, 2012.

2.4 Ph.D. Thesis

28. "Geometric Methods for Spectral Analysis," Xianhua Jiang, University of Minneosota, Department of Electrical and Computer Engineering, November 2011.

2.5 Software

http://www.ece.umn.edu/~georgiou/files/software.html
http://www.ece.umn.edu/~georgiou/files/HRTSA/download.html

3 Accomplished Research

The project succeeded at developing theory and tools for high-resolution analysis, for use in sensor networks, data mining, and spectral analysis. A key mathematical challenge was to introduce a suitable framework where questions regarding spectral uncertainty and the resolution of algorithms can be rigorously addressed. To this end, a geometric framework was developed based on a family of metrics which quantify distance between power spectral distributions in multivariable time-series. The geometric insights gained suggested new ways to aggregate data and refine various estimates from disparate data sets (e.g., obtained from a variety of sensors) using geometric means. They also suggested new techniques in filtering, estimation, and modeling. In particular, the concepts of geodesics provides models for time-varying power spectra and the concept of a geometric mean, with respect to the various metrics, has been evaluated in the context of estimating statistical quantities and model parameters. Examples and case studies of applying these concepts and relevant software are presented in the research publications. A description of the key concepts and of the software for high-resolution analysis that has emerged, building on earlier efforts and along with examples, is provided and maintained at the PI's website (http://www.ece.umn.edu/˜georgiou/files/software.html).

3.1 Geometric methods for spectral analysis

Most promising concepts that have emerged from this project include the notions of *geodesics* and *geometric means* in the space of power spectral distributions. Geodesics are natural models for modeling time-variability of power distributions. Paths on the space of distributions via geodesics can be constructed in complete analogy with Gauss' "least-squares" well-known and ubiquitous technique. The use of geodesics for modeling time-variability of power distribution of a process, provides significantly higher resolution. Geometric means on the other hand are natural in fusing together spectral information from various sources.

The research has succeeded in producing a geometric framework for multivariable time-series. This relies on suitable notion of distance. There are broadly two different rationale that lead to consistent, albeit different, geometries for power spectra. The first quantifies the ability to predict a time series using perturbed models. It leads to a Riemannian geometry for matrix-valued power spectra (corresponding to vector-valued time-series). The second is based on the Monge-Kantorovich transportation theory. In either direction, the definition and properties of the respective metrics, their geodesics, means, and relevant theory are being explained in Research Publications [1, 6, 7, 8, 10, 11, 14, 18, 27, 28]. Software tools (Matlab code) for and representative examples have been posted at the PI's website:

http://www.ece.umn.edu/˜georgiou/files/software.html
http://www.ece.umn.edu/˜georgiou/files/HRTSA/download.html

The family of metrics relate in unexpected ways to other, more traditional, information-theoretic concepts. More specifically, in [10] a relationship between the Kullback-Leibler divergence and the Rao metric, and of the Bures metric from quantum mechanics, the Hellinger distance, and the Wasserstein distance in optimal transport are linked together. In particular, the Wasserstein distance between Gaussian distributions can be efficiently computed in many dimensions via solving a convex optimization problem. The interplay between these metrics have studied as a tool for estimating statistics and parameter, in modeling time-series. More specifically, they are shown to have advantages in estimating structured covariance statistics [10] – a challenging problem in statistics (in shrinkage, instrumental variables, and error-in-variables models). Relevant software and their description along with examples are also provided in the aforementioned websites. It is also, a key contribution in a recently completed Ph.D. thesis (by Ms. Xianhua Jiang in [28]) and presented in [10].

3.2 Sparse and low-rank models

Research publications [12, 14] develop compressive sensing techniques for system identification and spectral analysis. In particular, techniques from robust statistics (LASSO, basis pursuit) are suitably adapted to solve problems in blind source deconvolution and in estimation of signals-in-noise, using sparse representation techniques. These can be used as an alternative to earlier high-resolution tools (detailed in the PI's website). This study was done in addition to the initially proposed plan for the project, and it was intended to investigate the merits of this new field. It was found that they are effective only when the very specific case where power spectra contain distinct lines (which are of interest). Robustness and reliability in these are often difficult to ascertain.

3.3 Fundamentals of feedback control

Research publication [9] revisited and extended a fundamental result of stochastic optimal control, that of the separation principle. The extension included stochastic processes which fall outside the class of the standard Gaussian case It was shown that "separation" of optimal-filtering and optimal-control is still valid when processes are certain type of semi-martingales with possible jumps. These results provided new insights to the control of systems driven by discontinuous processes modeling potential system-failures.

4 Personnel

Tryphon T. Georgiou, Professor
Ms. Xianhua Jiang, PhD student (received her PhD degree in 2011).
Mr. Lipeng Ning, PhD student.

5 Awards/Recognitions

The principle investigator, Tryphon Georgiou, was elected a *Foreign Member of the Royal Swedish Academy of Engineering Sciences, (IVA)* in June 2011.